

Mass Outflow in Active Galactic Nuclei: New Perspectives
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FUSE Observations of Warm Absorbers in AGN

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Abstract. In a survey of the UV-brightest AGN using the *Far Ultraviolet Spectroscopic Explorer (FUSE)*, we commonly find associated absorption in the O VI $\lambda\lambda 1032, 1038$ resonance doublet. Of 34 Type I AGN observed to date with $z < 0.15$, 16 show detectable O VI absorption. Most absorption systems show multiple components with intrinsic widths of $\sim 100 \text{ km s}^{-1}$ spread over a blue-shifted velocity range of $< 1000 \text{ km s}^{-1}$. With the exception of three galaxies (Ton S180, Mrk 478, and Mrk 279), those galaxies in our sample with existing X-ray or longer wavelength UV observations also show C IV absorption and evidence of a soft X-ray warm absorber. In some cases, a UV absorption component has physical properties similar to the X-ray absorbing gas, but in others there is no clear physical correspondence between the UV and X-ray absorbing components.

1. Introduction

Roughly 50% of all Seyfert galaxies show UV absorption lines, most commonly seen in C IV and Ly α (Crenshaw et al. 1999). X-ray “warm absorbers” are equally common in Seyferts (Reynolds 1997; George et al. 1998). Crenshaw et al. (1999) note that all instances of X-ray absorption also exhibit UV absorption. While Mathur et al. (1994; 1995) have suggested that the same gas gives rise to both the X-ray and UV absorption, the spectral complexity of the UV and X-ray absorbers indicates that a wide range of physical conditions are present. Multiple kinematic components with differing physical conditions are seen in both the UV (Crenshaw et al. 1999; Kriss et al. 2000) and in the X-ray (Kriss et al. 1996a; Reynolds 1997; Kaspi et al. 2001).

The short wavelength response (912–1187 Å) of the *Far Ultraviolet Spectroscopic Explorer (FUSE)* (Moos et al. 2000; Sahnou et al. 2000) enables us to make high-resolution spectral measurements ($R \sim 20,000$) of the high-ionization ion O VI and the high-order Lyman lines of neutral hydrogen. The O VI doublet is a crucial link for establishing a connection between the higher ionization absorption edges seen in the X-ray and the lower ionization absorption lines seen in earlier UV observations. The high-order Lyman lines provide a better constraint on the total neutral hydrogen column density than Ly α alone. Lower ionization species such as C III and N III also have strong resonance lines in the *FUSE* band, and these often are useful for setting constraints on the ionization level of any detected absorption. The Lyman and Werner bands of molecular hydrogen

also fall in the *FUSE* band, and we have searched for intrinsic H_2 absorption that may be associated with the obscuring torus.

We have been conducting a survey of the ~ 80 brightest AGN using *FUSE*. To date (March 1, 2001) we have observed a total of 57; of these, 34 have $z < 0.15$, so that the O VI doublet is visible in the *FUSE* band. In this presentation, I will be talking about the UV absorption properties of this sub-sample. A more extensive discussion of the full survey can be found in my review from last summer (Kriss 2000). Results on *FUSE* observations of individual interesting objects such as NGC 3516 (Hutchings et al. 2001), NGC 3783 (Kaiser et al. 2001), and NGC 5548 (Brotherton et al. 2001) can also be found in these proceedings.

2. Survey Results

Roughly 50% (16 of 34) of the low-redshift AGN observed using *FUSE* show detectable O VI absorption. None show H_2 absorption. I'd first like to review the spectral morphology of the O VI absorption features. We see three basic morphologies: (1) **blend**: multiple O VI absorption components that are blended together. This is the most common morphology (8 of 16 objects fall in this class), and the spectrum of Mrk 509 shown in Figure 1 illustrates the typical appearance. (2) **single**: single, narrow, isolated O VI absorption lines, as illustrated by the spectrum of Ton S180 in Figure 2. (3) **smooth**: this is an extreme expression of the “blend” class, where the O VI absorption is so broad and

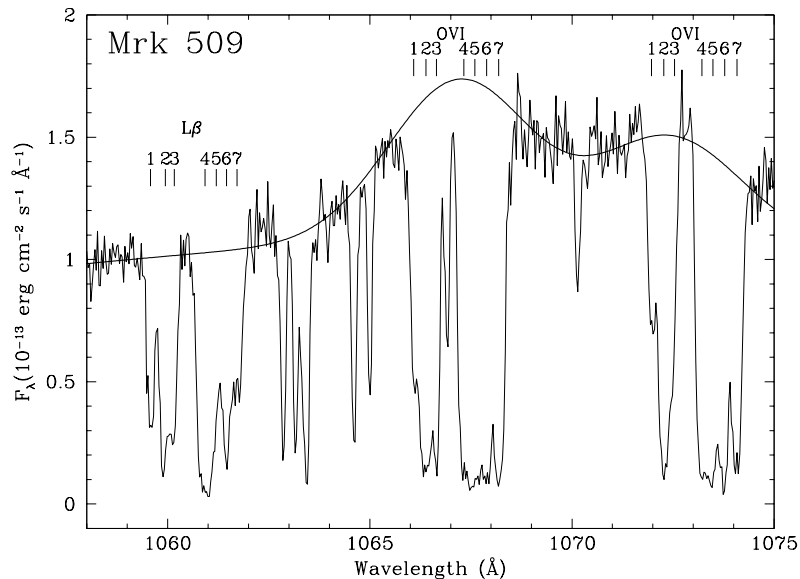


Figure 1. The $Ly\beta$ /O VI spectral region of Mrk 509, adapted from Kriss et al. (2000), illustrates the “blend” spectral morphology discussed in the text. The smooth, heavy line shows the local continuum comprised of a powerlaw continuum plus O VI emission from Mrk 509. Seven blended kinematic components are marked.

blended that individual O VI components cannot be identified. The spectrum of NGC 4151 shown in Figure 3 is typical of this class. (Note, however, that both broad smooth absorption as well as discrete components are often visible in this class.)

As shown in the summary of characteristics presented in Table 1, individual O VI absorption components have FWHM of 50–750 km s^{−1}, with most objects having FWHM < 100 km s^{−1}. The multiple components that are typically present are almost always blue shifted, and they span a velocity range of 200–4000 km s^{−1}; half the objects span a range of < 1000 km s^{−1}.

Table 1. Properties of O VI Absorbers in AGN Observed with FUSE

Name	# Comp	Type	Line Widths (km s ^{−1})	Velocity Spread (km s ^{−1})	Other UV Abs. ^a	X-ray Abs. ^b
I Zw 1	2	single	50	850	Y	...
NGC 985	1	smooth	100	1000
NGC 3516	5	blend	100	1000	Y	Y
NGC 3783	4	blend	300	1600	Y	Y
NGC 4151	3	smooth	100	1600	Y	Y
NGC 5548	6	blend	50	1300	Y	Y
NGC 7469	3	single	50	1000	Y	Y
Mrk 279	5	blend	100	1600	Y	N
Mrk 290	1	single	200	400	...	Y
Mrk 304	5	smooth	750	1500
Mrk 478	5	blend	50	2700	N	...
Mrk 509	5	blend	50	700	Y	Y
Mrk 817	2	blend	250	4000
PG1351+64	4	blend	100	2000	Y	...
Ton 951	1	single	40	200
Ton S180	3	single	50	300	N	N

^aUV reference: Crenshaw et al. (1999).

^bX-ray references: George et al. (1998); Reynolds (1997).

The 50% O VI absorption fraction is comparable to those Seyferts that show longer-wavelength UV (Crenshaw et al. 1999) or X-ray (Reynolds 1997; George et al. 1998) absorption. In Table 1 we make a detailed comparison to these UV and X-ray absorption studies. We can summarize this comparison in two ways: (1) all objects that have shown previous evidence of either UV or X-ray absorption also show O VI absorption in our *FUSE* observations; (2) of those objects showing detectable O VI absorption that also have previous UV or X-ray observations available, only 3 do not show X-ray absorption or longer-wavelength UV absorption. These three exceptions deserve some attention:

Ton S180 was observed simultaneously with *FUSE*, *Chandra*, and *HST* (Turner et al. 2001). As shown in Figure 2, the absorption features observed with *FUSE* are quite weak. At the resolution of the *HST* observations, which used the STIS low-resolution gratings, corresponding C IV and L α absorption would not be expected to be detectable. No X-ray absorption features are seen in the *Chandra* grating observation, which implies that either the total column

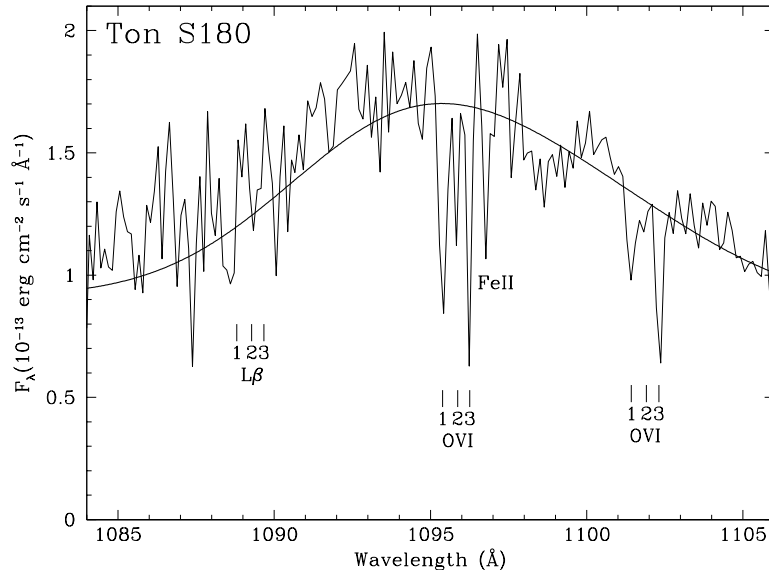


Figure 2. The $\text{Ly}\beta/\text{O VI}$ spectral region of Ton S180 shows the “single” absorption line spectral morphology discussed in the text. As in Fig. 1, the heavy smooth line shows the sum of a powerlaw continuum plus broad O VI emission. Three, narrow, isolated absorption components are visible in O VI. These are marked for both O VI and $\text{Ly}\beta$, even though no absorption is detected in $\text{Ly}\beta$. Ton S180 is also one of the objects in our sample for which we do not detect longer wavelength UV absorption or X-ray absorption (Turner et al. 2001).

density of the absorbing gas is very low, and/or that its ionization state is lower than that necessary to create X-ray absorbing species.

Mrk 478 was observed previously with *HST* using the FOS. As for Ton S180, these observations were low spectral resolution, so that weak C IV or $\text{L}\alpha$ absorption at the equivalent widths observed for O VI would not be detectable.

Mrk 279 shows strong $\text{Ly}\alpha$ absorption in an archival *HST* spectrum. However, the *ASCA* observation of Mrk 279 does not show evidence of a warm absorber (Weaver et al. 2001). This was a short observation, however, and total column densities of 10^{21} cm^{-2} could easily be present, which would be detectable in *Chandra* grating observations.

3. Discussion

The multiple kinematic components frequently seen in the UV absorption spectra of AGN clearly show that the absorbing medium is complex, with separate UV and X-ray dominant zones. In some cases, the UV absorption component corresponding to the X-ray warm absorber can be clearly identified (e.g., Mrk 509, Kriss et al. 2000). In others, however, *no* UV absorption component shows physical conditions characteristic of those seen in the X-ray absorber (NGC 3783: Kaiser et al. 2001; NGC 5548: Brotherton et al. 2001). One

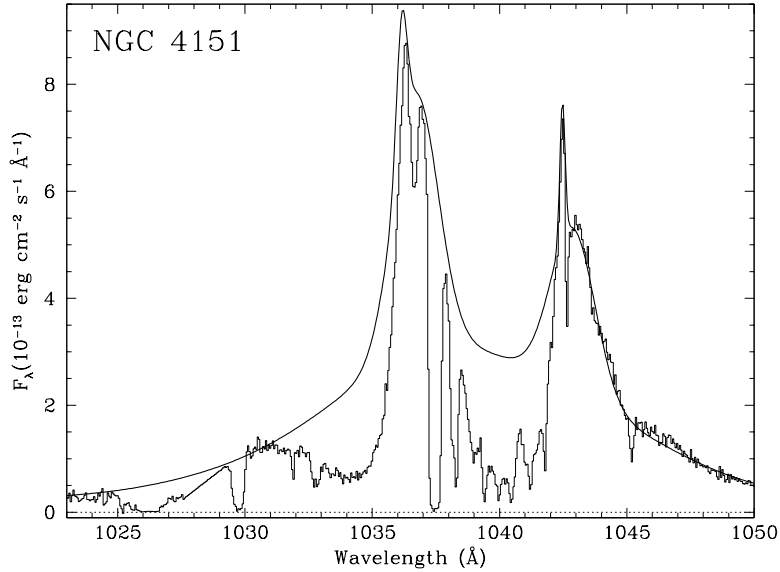


Figure 3. Our FUSE observation of NGC 4151 caught this galaxy in a low-luminosity state. The O VI region is dominated by narrow-line emission, but smooth, broad absorption illustrating the “smooth” morphology discussed in the text. The heavy, smooth solid line shows the modeled total emission from a powerlaw continuum plus weak broad-line and strong narrow-line emission.

potential geometry for this complex absorbing structure is high density, low column UV-absorbing clouds embedded in a low density, high ionization medium that dominates the X-ray absorption. As discussed by Krolik & Kriss (1995; 2001), this is possibly a wind driven off the obscuring torus. At the critical ionization parameter for evaporation, there is a broad range of temperatures that can coexist in equilibrium at nearly constant pressure; for this reason, the flow is expected to be strongly inhomogeneous. What would this look like in reality? We will not soon get a close-up look at this aspect of an AGN, so it is instructive to look at nearby analogies. The HST images of the pillars of gas in the Eagle Nebula, M16, show the wealth of detailed structure in gas evaporated from a molecular cloud by the UV radiation of nearby newly formed stars (Hester et al. 1996). In an AGN one might expect a dense molecular torus to be surrounded by blobs, wisps, and filaments of gas at various densities. It is plausible that the multiple UV absorption lines seen in AGN with warm absorbers are caused by high-density blobs of gas embedded in a hotter, more tenuous, surrounding medium, which is itself responsible for the X-ray absorption. Higher density blobs would have lower ionization parameters, and their small size would account for the low overall column densities.

In summary, we find that O VI absorption is common in low-redshift ($z < 0.15$) AGN. 16 of 34 AGN observed using *FUSE* show multiple, blended O VI absorption lines with typical widths of $\sim 100 \text{ km s}^{-1}$ that are blueshifted over a velocity range of $\sim 1000 \text{ km s}^{-1}$. With three exceptions, those galaxies in our

sample with existing X-ray or longer wavelength UV observations also show C IV absorption and evidence of a soft X-ray warm absorber. In some cases, a UV absorption component has physical properties similar to the X-ray absorbing gas, but in others there is no clear physical correspondence between the UV and X-ray absorbing components.

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